



## Cosmic ray spectral hardening due to dispersion of source injection spectra

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**Abstract:** The cosmic ray (CR) energy spectra measured with ATIC, CREAM and PAMELA showed that there is remarkable hardening for rigidity of several hundred GV. We propose that this hardening is due to the superposition of spectra from a population of sources, e.g., supernova remnants (SNRs), whose injection spectral indices have a dispersion. Adopting proper model parameters the observational data can be well explained. It is interesting that the injection source parameters are similar with that derived from gamma-ray observations of SNRs, which may support the SNR-origin of CRs. Furthermore this mechanism provides an alternative explanation of the “ankle-cutoff” structure of the ultra high energy CR spectra.

**Keywords:** cosmic rays, energy spectra and composition, supernova remnants

## 1 Introduction

The origins, acceleration processes, propagation and interactions of cosmic rays (CRs) are still open questions, even after about one century since the discovery of CRs. It is generally believed that Galactic CRs (GCRs) are accelerated by the astrophysical shocks like supernova remnants. After the production, GCRs are then injected into the interstellar space and propagate diffusively in the Galactic magnetic field. During the propagation, CRs will interact with the interstellar medium, radiation field and magnetic field, which result in spallation and energy loss of the particles, and the production of secondary particles (see [1] for a review).

In recent years more and more accurate data of the CR spectra and composition are available. The balloon-borne experiment Advanced Thin Ionization Calorimeter (ATIC) measured the CR spectra of various species of nuclei and showed the deviation from single power-laws of the spectra [2, 3]. ATIC data also revealed the difference between proton and Helium spectra. Another balloon experiment Cosmic Ray Energetics And Mass (CREAM) measured the energy spectra of the major species from proton to iron with relatively high precision, and reported a remarkable hardening of the spectra of most heavy species at  $\sim 200$  GeV/nucleon [4, 5]. Such spectral features were confirmed most recently by the satellite experiment Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA). PAMELA measured the proton and Helium spectra up to rigidity 1.2 TV with high precision, and the

data show clearly a spectral hardening at rigidity  $\sim 200$  GV [6], which is basically consistent with the results of CREAM and ATIC. The spectral indices of proton and Helium were also found significantly different.

The hardening of the CR spectra challenges the conventional idea that the spectra below the so-called “knee” are simple power-laws. More complicated scenarios of CR origin, acceleration or propagation are needed to explain the data. Models possibly to explain such a spectral hardening include the multi-component sources [7], or the nonlinear particle acceleration scenarios where the feedback of CRs on the shock is essential (e.g., [8, 9, 10, 11]).

In [12] we propose that the hardening of the observed CR spectra is due to the dispersion of the injection spectra of a source population such as supernova remnants (SNRs). The basic fact that the superposition of a series of spectra with different power-law indices would result in an asymptotic hardening of the final spectra of CRs was recognized long ago [13]. Such an effect was also employed to explain the “GeV excess” of Galactic diffuse  $\gamma$ -rays observed by EGRET [14, 15].

The observations of various kinds of candidate high energy CR sources such as SNRs, active galactic nuclei and gamma-ray bursts, show indeed there is significant dispersion of the source spectra. For example, the spectral modeling of the  $\gamma$ -ray emission from several SNRs observed by Fermi and ground-based Cherenkov telescopes show that the low and high energy spectral indices are  $\gamma_1 \approx 2.15 \pm 0.33$  and  $\gamma_2 \approx 2.54 \pm 0.44$ , assuming a hadronic scenario of the  $\gamma$ -ray emission [16]. In the follow-

ing we will show how such a scenario can naturally explain the observational data of the CR spectra.

## 2 Model and result

We assume that GCRs are originated from SNR-like sources. The injection spectrum of each source is assumed to be a broken power-law function of rigidity. The spectral indices are assumed to be Gaussian distributed around the average values. The break rigidity  $R_b$  is shown to be several to tens of GV [16]. Here we assume the logarithm of  $R_b$  is randomly distributed in some range. The normalization of each source is derived assuming the same total energy of CRs above 1 GeV for all sources. The detailed parameters are given below, according to the fit to the observational CR data.

The CR propagation is calculated with the public GALPROP<sup>1</sup> code [17]. In this work we adopt the diffusive reacceleration frame of the propagation model, with the main parameters  $D_0 = 5.8 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$ ,  $\delta = 0.33$ ,  $v_A = 32 \text{ km s}^{-1}$  and  $z_h = 4 \text{ kpc}$ . The input source spectra are adopted as the superposed ones of many sources. The B/C ratio is found to be well consistent with data and insensitive to the source spectrum.

For the low energy spectra (below  $\sim 30 \text{ GV}$ ), the force-field approximation is adopted to model the solar modulation effect [18]. The modulation potential  $\Phi$  varies from  $\sim 200 \text{ MV}$  to  $\sim 1400 \text{ MV}$ , depending on the solar activity. The modulation potential was estimated to be  $450 - 550 \text{ MV}$  for the time when the proton and Helium data used in this work were recorded by PAMELA [6]. In this work we adopt  $\Phi = 550 \text{ MV}$  for proton and Helium. For Carbon, Oxygen and Iron nuclei the low energy data used are from HEAO3, for which we adopt  $\Phi = 750 \text{ MV}$ . A higher modulation potential for HEAO3 was also found in [19].

We further adopt a break/cutoff at high rigidities ( $\sim \text{PV}$ ) to approach the “knee” of the CR spectra. The physical models of the knee include the propagation/leakage effect from the Galaxy, or interactions with background particles [20]. Phenomenologically we adopt two kinds of cutoff/break to model the knee structure of the total spectra: a sub-exponential cutoff case with the energy spectrum above the injection break  $R^{-\gamma_2} \exp[-(R/R_c)^{1/2}]$ , and a broken power-law case with energy spectrum above the injection break  $R^{-\gamma_2}(1 + R/R_c)^{-1}$ . In both cases we assume the break rigidities  $R_c$  of different nuclei are the same, i.e., the break energies are  $Z$ -dependent. The parameter  $R_c$  is adopted to be a constant instead of that varying for different sources. This assumption is reasonable for the propagation/leakage and interaction models. However, we may note that for the acceleration limit models, the break energies of different sources should have a dispersion. It is tested that the results with dispersion of the break rigidities are similar to that with a proper constant  $R_c$ .

The calculated energy spectra of proton, Helium, Carbon, Oxygen, Iron and the total spectrum, together with the ob-

servational data are shown in Figure 1. The parameters used in the calculation are compiled in Table 1. We find relatively good agreement between the model calculation and the observational data. It is interesting that the injection source parameters are similar to those inferred from the  $\gamma$ -ray observations of SNRs. This might be evidence that SNRs are the sources of GCRs below  $\sim \text{PV}$ .

Note that our model prediction is a gradual hardening of the CR energy spectra, which seems to be consistent with the overall structures of data in a wide energy range. However, if we focus on the detailed structures revealed by individual experiment, we may still find some inconsistency. For example the PAMELA data show a very sharp dip at  $\sim 200 \text{ GV}$  and a gradual softening below the break rigidity [6]. The CREAM data indicate that all species of nuclei experience a hardening at  $\sim 200 \text{ GeV/n}$  [5]. The very fast break of the spectra shown in both PAMELA and CREAM data cannot be well reproduced in the present model. Before giving a conclusive judgement about this issue, we may need future better measurements of wide energy band spectra by e.g., the Alpha Magnetic Spectrometer (AMS02<sup>2</sup>) and the Large High Altitude Air Shower Observatory (LHAASO, [21]).

## 3 Impact on secondary particles

The hardening of the primary CR particles should have imprints on the secondary particles such as positrons [22], diffuse  $\gamma$ -rays, and antiprotons [23]. In [24] a systematic study of the secondary particles including B/C, antiprotons and diffuse  $\gamma$ -rays in different scenarios of the spectral hardening was performed. As an example, here we calculate the predicted hadronic-origin diffuse  $\gamma$ -ray fluxes in this scenario. The  $\gamma$ -ray production spectrum from  $pp$  inelastic interactions is calculated using the parameterization given in [25]. The contribution to  $\gamma$ -rays from heavy nuclei in both the projectile and target particles is approximated with a nuclear enhancement factor  $\epsilon_M = 1.84$  [26]. We show in Figure 2 the ratios of the hadronic component of the diffuse  $\gamma$ -ray fluxes between our model expectation and that of the traditional single power-law CR spectrum. It is shown that the  $\gamma$ -ray flux will also experience a hardening above  $\sim 50 \text{ GeV}$ . The most remarkable hardening effect will be in the very high energy range ( $> \text{TeV}$ ), which is out of the capability of Fermi telescope.

Since the total diffuse  $\gamma$ -rays consist with hadronic, leptonic and the extra-galactic components, the hadronic one is not a direct observable. As we know that in the Galactic plane the diffuse  $\gamma$ -rays should be dominated by the hadronic component [27], we expect such a predication can be tested with high precision diffuse TeV  $\gamma$ -ray observation of the Galactic plane.

For positrons and antiprotons we will expect similar results, however, the quantitative effects should depend on

1. <http://galprop.stanford.edu/>

2. <http://ams.cern.ch/>

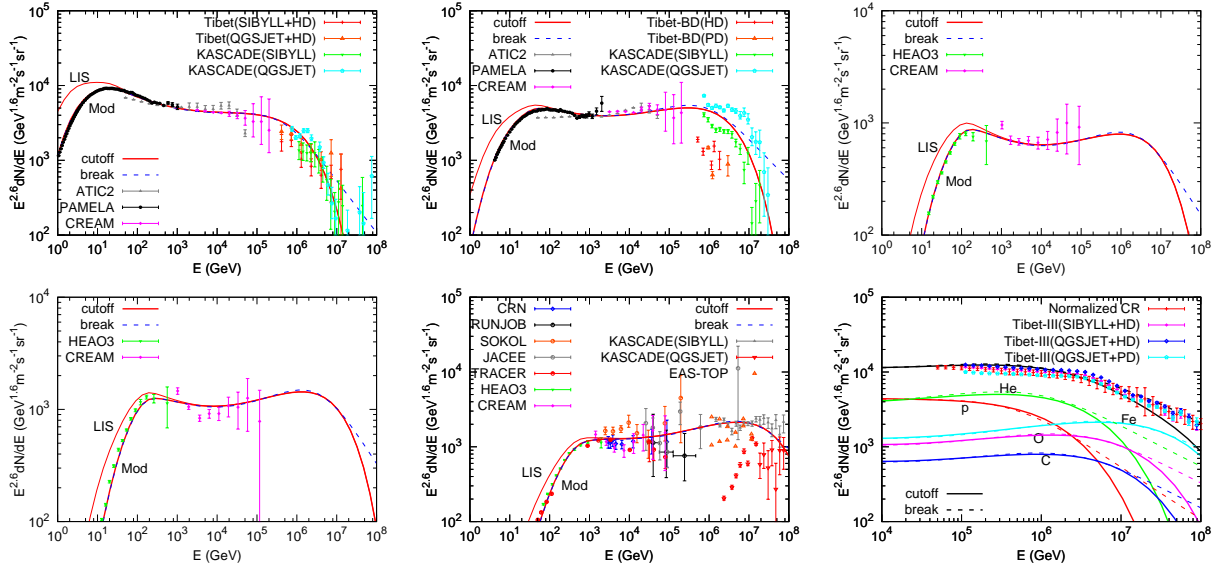


Figure 1: Energy spectra of proton (top-left), Helium (top-middle), Carbon (top-right), Oxygen (bottom-left), Iron (bottom-middle) and the all-particle one (bottom-right). The solid line in each panel represents a sub-exponential cut-off behavior of the high energy spectra around the knee region, while the dashed line is for broken power-law type. For references of the data please refer to [12].

Table 1: Source parameters: injection spectra  $\gamma_1$ ,  $\gamma_2$  and break rigidity  $R_b$ , high energy cutoff rigidity  $R_c$  and solar modulation potential  $\Phi$ .

		$\gamma_1$	$\gamma_2$	$R_b$ (GV)	$R_c$ (PV)	$\Phi$ (GV)
cutoff	p	$1.95 \pm 0.20$	$2.52 \pm 0.28$	[5, 30]	0.5	0.55
	He	$1.95 \pm 0.20$	$2.50 \pm 0.33$	[5, 30]	0.5	0.55
	C,O,Fe	$1.95 \pm 0.20$	$2.58 \pm 0.35$	[5, 30]	0.5	0.75
break	p	$1.95 \pm 0.20$	$2.52 \pm 0.25$	[5, 30]	0.5	0.55
	He	$1.95 \pm 0.20$	$2.50 \pm 0.30$	[5, 30]	0.5	0.55
	C,O,Fe	$1.95 \pm 0.20$	$2.58 \pm 0.32$	[5, 30]	0.5	0.75

the source distribution and propagation model. The current antiproton data from PAMELA can not probe such a hardening effect yet. Also the PAMELA positron excess above several GeV should not be originated from the hardening of the CR proton and Helium spectra.

#### 4 Alternative explanation of the ultra high energy CR spectra?

We also note that the dip-cutoff structure shown in Figure 1 is very similar to the ankle and Greisen-Zatsepin-Kuzmin (GZK) cutoff structure of the ultra high energy CRs (UHECRs). If the UHECRs are originated from a population of sources instead of a major one, it is expected that the UHECR spectra should also suffer from such a hardening due to the superposition effect. It might provide us an alternative point of view to understand the observational energy spectra of UHECRs.

We show an illustration of the predicted UHECR spectra, together with the HiRes data [28], in Figure 3. Here the

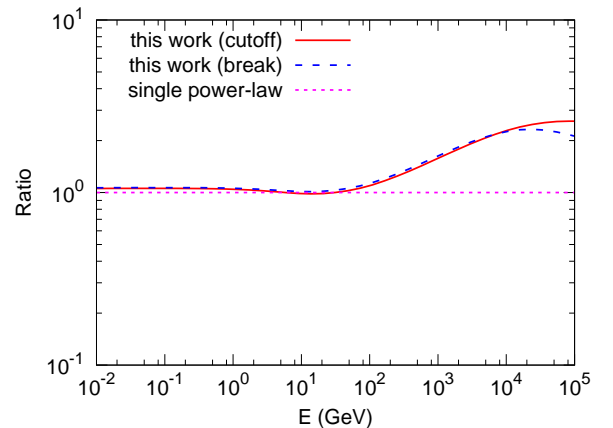


Figure 2: Ratio of the hadronic component of the diffuse  $\gamma$ -rays between the dispersion scenario expectation and the single power-law model.

chemical composition of UHECRs is assumed to be pure protons. The injection spectrum of UHECRs is adopted to

be a broken power-law function with an exponential cut-off [29]. The logarithm of break energy  $\log(E_b/\text{eV})$  is assumed to be uniformly distributed in [17, 18], and the spectral index is  $2.0 \pm 0.2$  below  $E_b$  and  $3.6 \pm 0.6$  above  $E_b$ . The cutoff energy  $E_c$  is adopted to be  $5 \times 10^{19}$  eV. The result shows a good description of the observational data.

If the UHECRs are produced at cosmological distances, however, the interactions between UHECRs and the cosmic background photons are unavoidable [29]. Therefore if the superposition effect is responsible for the shape of the UHECR spectrum, we may in turn expect that UHECRs are produced locally or even in the Galaxy [30]. More generally, it is possible that both the superposition and the interaction effects are in operation to give the ankle-GZK structure of UHECRs.

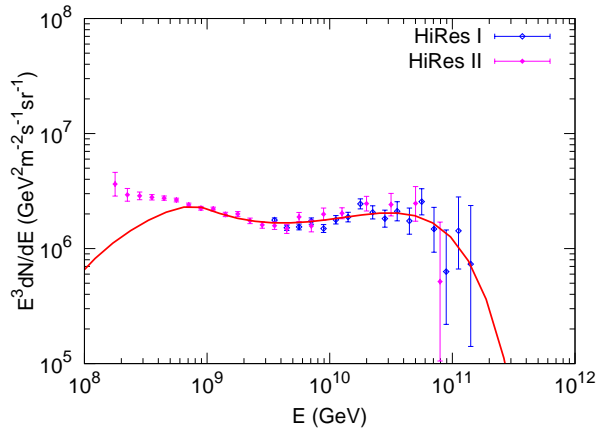


Figure 3: Calculated energy spectra of UHECRs for pure protons, compared with the HiRes data [28].

## 5 Summary

In summary we propose that the superposition of the energy spectra from CR sources with a dispersion of injection spectra is responsible for the recently reported hardening of the CR spectra. If the CRs are indeed originated from a population of sources instead of a single major source (e.g., [31]), such an asymptotic hardening effect due to dispersion of source properties is inevitable. It is interesting to note that the source parameters derived are similar to that inferred from  $\gamma$ -ray observations of SNRs, which might support the SNR-origin of GCRs below the knee. Finally we discuss the same mechanism as an alternative explanation of the ankle-GZK structure of UHECR spectra.

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